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NASA Contractor Report 182140

Industrial Processes Influenced by Gravity

(NASA-CR-182140) INDUSTRIAL PROCESSES INFLUENCED BY GRAVITY Final Report (Case Western Reserve Univ.) 47 p CSCL 22A
N88-26497
Unclas
G3/29 0149967

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June 1988

Prepared for
Lewis Research Center
Under Contract C-21066-G

National Aeronautics and
Space Administration

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INDUSTRIAL PROCESSES INFLUENCED BY GRAVITY

By

Simon Ostrach

INTRODUCTION

The potential advantages of a low-gravity environment are:

1. The levitation and isolation of large samples for containerless processing.

2. The reduction of phase separations and particle settling.

3. The reduction of buoyancy-driven convection

Concomitantly, surface tension becomes an important force for fluid behavior when fluid interfaces exist.

The existing Microgravity Science and Applications and Commercial Development of Space Programs include tasks related to each of these, with the primary emphasis on the third, i.e., to find the influence of reduced convection on crystal quality. Levitation systems and containerless processing of materials are examples of work based on the first category and directional solidification of two-phase (or multi-phase) composite materials and biological separations are examples of the second. Although, a great deal has been learned about the low-gravity environment and some potentially interesting applications have been identified, no truly significant results have been obtained. It, therefore, appears worthwhile to consider broadening both the research and applications programs in order to expand the base from which outstanding new results might be possible.

In considering new directions for investigation, it should be noted that the nature of most chemical and physicochemical operations is mostly determined by transport phenomena. Among such operations, heterogeneous transformations in liquids and gases are of primary importance. By heterogeneous is meant

chemical and physicochemical reactions or transformations that take place on certain surfaces, such as phase boundaries and surfaces with catalytic properties. Under this broad definition there is included: all catalytic reactions, adsorption, desorption at solid and liquid surfaces; dissolution, and precipitation of crystals from solutions and melts; electrochemical reactions at electrode surfaces that are immersed in electrolytes; evaporation, sublimation, and condensation; gas adsorption by liquid and solid surfaces, etc. Many of these phenomena are vital elements in diverse processes in the chemical, pharmaceutical, food-processing, and biotech industries. Thus, consideration of topics as indicated above would extend commercialization possibilities beyond just materials processing, the area currently receiving primary attention.

Phase separations and mixing are inherent to many of the phenomena mentioned above and, it is clear, that phase interactions will be different in a low-g environment compared to those on earth. Separation is one of the key unit operations in industry to obtain end products. Table 1, from Ref. 1, lists many industrial separation operations and it can be seen that gravity is an important factor in a large number of them. In a recent book, Ref. 2, to determine potential energy savings in separating fluid mixtures it was suggested that the methods with best short-term potential include: distillation, membrane separation, adsorption, extraction, and crystallization. To obtain improvements it is recommended that fundamental studies are needed in: theory development, data-base expansion, development of heat-mass-momentum transfer models, physicochemical effects at phase boundaries, and scale-up techniques. Low-g was not considered an option, but the same fundamental studies could be applied under that condition as well.

In some processes, it is desirable to keep a component in suspension for nucleation and growth or to increase process residence times. Clearly, low-g would enhance those phenomena. Furthermore, separation of complex mixtures into their component parts is particularly important in biomedical and pharmaceutical applications. The lack of satisfactory separation techniques, in many cases, is the limiting factor that impedes research involving cells, cell components, and macromolecules. Most

separation techniques are based on either very nonspecific characteristics (e. g., density) or on characteristics so highly specific that the method can be used only on previously purified materials. Some of the currently used techniques, like continuous-flow electrophoresis and phase partitioning, in which it is possible to start with a mixed population of cells or proteins and sort them into categories which are specific as well as biologically meaningful are impeded by gravity-related effects. Some of these are being investigated at low-g, but others may also be likely.

The mixing of immiscible fluids followed by solidification holds promise for producing new and important composite materials. Thus, one major area of emphasis in the present report will be on phase separations and mixtures. This subject, which has not received comprehensive and concentrated attention in the space research program represents not only areas which are of scientific interest but also ones which open commercialization opportunities to many more diverse industries than has been the case heretofore.

Other topics to be given attention herein are those in which surface tension plays an important role. Coatings and fibers, thin films, ceramics and glass formation, and atomization are some industrial applications of that type. The CWRU group has done the most extensive research on capillarity effects and, as a result, may be able to give new insights to such phenomena.

SYNOPSIS

The present report advocates microgravity as an avenue for industrial processing research. Industrial processes that are influenced by gravity and/or interfacial phenomena are identified and ideas are presented that will benefit from careful study. The obvious progression of events is research, understanding, and implementation. The last might be in terms of microgravity processing, but this may well not occur in the near future.

It should be noted that most industrial processes were developed empirically and as long as the companies were profitable no changes were made. With the many global challenges to U. S. industries it appears necessary to give scientific scrutiny to the processes so that they can be better understood

in order to improve them to meet the competition. Since gravity and interfacial phenomena play important roles in many industrial processes, many problems could be understood more fully if microgravity experiments were conducted. The knowledge gained could facilitate improvements in terrestrial processing in the near term and could indicate potentials for longer term low-g processing.

The material presented herein starts out with an outline of the study phases and then proceeds to an introduction that indicates more fully the need for low-gravity processes research. Then industrial processes, phenomena, and devices are described in two main sections: multiphase mixtures and surface-tension effects. The first of these is further subdivided into gas-solid, gas-liquid, liquid-solid, and liquid-liquid sections.

Finally, conclusions and recommendations are presented.

STUDY PHASES

To identify the industrial processes that are influenced by gravity the study was developed in a number of phases:

A. Information Acquisition

1. On-line search

(a) DIALOG-Engineering Societies Library, N.Y.

(i) COMPENDEX

(ii) EI Engineering Meetings

(iii) AEROSPACE

2. National Technical Information Service Published Searches

3. Government Report Announcement (GRA) and Index (GRI)

4. Texts, monographs, and articles

(a) Chemical processing

(b) Separations

(c) Films and coatings

(d) Two-phase flows

(e) Supercritical Fluid Extraction

B. Document Review

C. Outreach

1. Meetings with specialists in industry

2. Personal contacts

D. Identification of Candidate Processes and Evaluation

E. Report Preparation

CONCEPTS AND IDEAS

A. Introduction:

From the literature and personal discussions, it is clear that little attention has been given to the effect of gravity on chemical processes on earth. In designing unit operations, since gravity was not a variable it was not given any particular consideration, although it did appear in some of the equations. Recently, some work has appeared in which high-g effects are studied in centrifuges. With the advent of space research forward-looking survey articles, Refs. 3 and 4, for example, more or less stressed the areas that are currently under investigation. Some people from industry said that they had tried with no success to consider how space research could be of benefit to them. In effect, the situation in most industry seems similar to that in the early days of crystal growing. Most of

there is reason for space experiments. At very least, terrestrial processing may be improved in this way.

B. Multiphase Mixtures

On earth, multiphase mixtures generally segregate or separate because of density differences. At low-g, dispersions and foams are formed more readily and are more stable with respect to segregation and separation. Those may be advantageous or deleterious for different processes depending on their objectives. Multiphase mixtures are ubiquitous in industrial processes. Such processes are built up of unit operations that can be studied and treated separately, irrespective of the process itself. Thus, for example, the principles of adsorption are the same whether this unit operation is used to remove soluble components from a flue gas or as a step in the production of a fertilizer. There are many ways in which material on this subject can be presented. Here, we will essentially focus on two-phase mixtures and will categorize the material in sections on gas-solid, gas-liquid, and liquid-liquid mixtures. Such a classification makes it easier to understand the rationale for the ideas.

I. Gas-Solid

Adsorption-desorption, drying, fluidized beds, flotation are among the operations involving gas-solid mixtures in various industrial processes. The diversity of problems and physical situations cause this subject to be extremely complex. As a consequence, most real systems are described by empirical and semiempirical relations.

1. Catalysts: In Ref. 5 it is pointed out that there is a strong incentive currently for the development of new catalysts to process fuels and chemicals. This is a vital area of need for the entire chemical industry. In particular, there is a great deal of interest in amorphous materials as catalysts because they show higher activity and selectivity than crystalline materials, Ref. 6. Because of the differences in nucleation, growth and particle interaction between one-g and low-g, preparation of amorphous catalytic solids in space may be worthwhile. Investigation could be made of different surface energetics created by rapid quenching of gaseous precursors to fine solid

particles. This could result in homogeneous multielement solid, non-crystalline phases that are not possible on earth. The role of surface tension could also be important in rapid phase changes from gas to liquid to solid.

Calcination is a key step in conventional catalyst preparation. This typically involves heating an inorganic compound to convert solid A to solid B + gas. The evolution of gas leads to the development of an internal pore structure and external surface area. The gas evolution could be different in a low-g environment which could result in a class of catalytic solids with structures unlike those at one-g. The diminished driving force for gas evolution could lead to the retention of larger and more accessible pore structures during calcining. The calcining process is common to many processes that do not produce catalysts. The formation of lime from limestone is an example. A generic study would be useful for many industrial processes.

The importance of catalyst preparation and use in chemical processes is given in Ref. 6. Catalysis directly or indirectly affects roughly 20% of the GNP of the United States. Annual use is about 5 billion pounds. Amounts used can vary from grams in specialty reactions to many tons in one catalytic reactor. There is a need to replace constantly spent catalysts or fines that are blown out of cyclones in reactor vent systems. Catalysts are used in petroleum refining, petrochemical production, food processing and biotechnology.

Commercial catalyst manufacturers include Degussa, Norton, Union Carbide, Johnson-Matthey, Sohio, and Ferro.

2. Chemical Vapor Deposition (CVD): CVD is used to coat surfaces by depositing thin films generated in high temperature chemical processing of a gas phase chemical. At low-g, reduced sedimentation could lead to more uniform coating deposition. Sedimentation at one-g is a problem particularly with dense metal containing gases, such as tungster for example.

This process is used to prepare corrosion resistant coatings, specialty electronic coatings for thin film semiconductors and computer chips, and catalytic surfaces. The use in nuclear, alternate energy sources, such as photovoltaic and thermoelectric, and vessel cladding put it in a class of

small but important value-added processing.

3. **Electrochemistry:** There is a growing interest in organic chemical processing in electrolytes using hydrogen generation at a cathode. Terrestrially, the gas readily escapes from the active front surface of the electrode which causes loss in efficiency. Synthesis at low-g should make it possible to maximize the energy efficiency and throughput because of the reduced rise of the active hydrogen through the liquid electrolyte.

Since electrochemical synthesis is a new and developing field, the impact is difficult to predict. However, the technology could have spin offs in other electrochemical systems such as fuel cells, batteries, and gas-generating cells. Groups with interest in this area would be the CWRU Electrochemical Center, Diamond Shamrock, and the Office of Naval Research.

4. **Fluidized Beds:** The use of packed beds containing solid particles as catalysts or heat exchangers is very common in the chemical industry. In fact, this area of processing is as important as most any other including catalysis and separations. In packed beds a gas enters the bottom and passes out the top. As the gas velocity increases the point is reached where the bed expands and offers less flow resistance. When the particles become freely suspended the bed attains the fluidized state. At this point, the bed behaves like a well-stirred boiling liquid. The result is a system with good gas-solid contact efficiency and good heat transfer capability. The latter is especially important in exothermic reactions wherein heat generated in the process could melt a reactor in the absence of fluidization.

The maximum fluidization velocity required to expand the bed is a function of g at both low and high particle Reynolds numbers. The other variables are particle diameter, densities of particles and fluid, and gas velocity.

A typical example is the fluidization of hematite (Fe_2O_3) particles of 100 m diameter in hydrogen at 900°C at 1 atmosphere. The maximum velocity, U_m, is 0.014 mps. The theoretical limit of fluidization velocity, U_t/U_{min}, where U_t is the terminal rising velocity ranges from 10 for large to 90 for small particles. The upper limit in practice is that point at

which there is excessive particle loss out the stack.

Because of the direct effect of g on such calculations it should be possible to operate fluidized beds at quite low velocities to carry out reactions at low-g relative to those at one-g. Chemical synthesis aboard spacecraft or on the moon could be greatly enhanced by use of fluidized beds which require small gas throughput. This minimizes the need for gas. A drawback, however, is the obvious inverse relationship between gas input and product output.

Fluidized beds are used by all petroleum refining and petrochemical companies. Usage is becoming popular in coal burning power plants to remove sulphur, calcination of natural minerals, reduction of iron ore and others. Manufacturers include Dorr Oliver, Keeler Dorr Oliver, and Glitsch.

5. **Cyclones:** Use of cyclones for gas-solid separation is closely allied with fluidized bed reactors. The cyclone is a means of removing paraticles from a gas laden exit stream and returning them to the reactor. The terminal falling velocity of the smallest particle just retained in the cyclone is a function of g. Because of this at one-g the limit on efficiency of industrial cyclones is on the order of 5-10 μm in particle size. At low-g this velocity would be decreased and the ability to handle submicron amorphous particles would be improved.

It would seem possible thus to prepare sub-micron amorphous catalytic particles in a fluidized bed chemical reaction with effluent particles retained in cyclones.

Cyclones are used in the same applications as fluidized beds and also for pollution abatement in power plants, refuse burners, and calciners. Major manufacturers include General Electric, Dorr Oliver, and Siveco.

6. **Spouting Bed Vessels:** The spouting bed technique is used with solids which are too coarse to be handled in fluidized beds, but too fine to be handled in an ordinary gravity bed. Gas enters a bed of loosely packed particles. At a critical velocity spouting begins and the gas-solid mixture goes to the top of the bed and overflows into a surrounding annulus, where the solids fall as in an ordinary gravity bed. The minimum velocity for

spouting is proportional to $g^{1/2}$.

Typically, this process is used for air drying of grain, sand, shale, gravel, and wood chips. Its applications, thus, are in agriculture, building, and mineral processing. Heat transfer is better than with direct heat rotary dryers.

II. Gas-Liquid

This is perhaps the most interesting topic because it appears in so many different processing schemes. Gas-bubble-melt interactions are important in such operations as copper converting, vacuum degassing, and argon stirring in metals processing. Aerosols, foams, and boiling also involve bubble-liquid interactions as well as others described in this section.

Gravity enters into adiabatic gas-liquid configurations in a number of ways. The gas-liquid interface is uniquely dependent on the value of the local acceleration of gravity. Other system variables such as container geometry, contact angle, relative densities of the two phases and the surface tension are also important. As g is reduced, surface-tension effects dominate the determination of the shape and motion of the interface. These effects are not just limited to static situations but include the dynamics of interfaces as well. The structure and distribution of the two phases depend on the magnitude of the buoyancy force.

From a practical viewpoint, there is a desire to predict the overall rate of reaction between the dispersed (bubble) phase and the liquid or to characterize the fluid motion, such as the circulation induced by a stream of gas bubbles. Scientific interest lies in the understanding of the distribution of the gas and liquid phases as a function of flow quality, phase velocities, and geometry. The pressure drop and transition among flow regimes are not known under low-g conditions. The heat and mass transfer and reactions in such multiphase systems must also be known. Of interest are such matters as the onset of bulk boiling, the shape of the nucleate heat transfer curve, low-g heat transfer coefficients, and interfacial mass transfer rates.

Evaporation and condensation from augmented surfaces can also benefit from study at low-g conditions by obtaining a more fundamental understanding of these processes at gas-liquid

interfaces. In particular, it would be valuable to determine how they are affected by fluid and thermal properties, gas-phase characteristics, the wetability of a heated surface, and the surface geometry near the interface.

The rapid cooling of molten metals can be considered in a separate category. Here, the goal would be to utilize the space environment to see if significant improvements could be made in the production of certain alloys.

The reduction of convective heat transport and the increased importance of surface-tension forces are expected to lead to unique transport processes and unusual fluid behavior.

Gas absorption is a unit operation where one or more components of a gas mixture are dissolved in a liquid. The reverse of absorption is gas desorption or stripping, where the transfer takes place from the liquid mixture to the gas, see Ref. 7. Fig. 1 from Ref. 7 shows typical gas absorption equipment. In stripping gas entering the vessel at the bottom sweeps a dissolved species out the top so the vessels are similar.

1. **Gas Bubbles in Liquids:** The study of bubbles (and drops) can be divided into investigations of their formation or disappearance, by mass transfer processes, and of their behavior once formed. The categories can be made in another way, viz., into systems of a single bubble, two or more bubbles with some interaction with each other, and swarms of them engaged in collective action as dispersion of one phase in another. The less populous systems are most often the focus in basic disciplines, while dispersions receive the attention of applied scientists and engineers.

The motion of bubbles in liquids is characterized by dimensionless parameters: the Reynolds number, Re, the Eotvos number, $E = g\ell^2(\rho-\rho_\infty)/\sigma$, and the Morton number, $M = g\mu/\rho\sigma^3$, where ℓ is a characteristic length, ρ the fluid density, σ the surface tension, and μ is the fluid viscosity. The latter two are directly related to the gravitational acceleration, g. The bubble volume, V, at detachment from a point source orifice in an inviscid liquid for isothermal and constant flow condition is, Ref. 8, proportional to $G^{1.2}g^{-0.6}$, with G the flow in volume per unit time. The bubble frequency is

proportional to $G^{-0.2}$. The consequences of this are that if the volume is be be kept the same size at low-g to avoid huge bubble formation and if subscript 1 denotes one-g and 2 low g

$$G_2 = G_1[(g_1/g_2)^{-0.6}]^{1/1.2}$$

or

$$G_2 = G_1 g_2^{0.5}$$

Thus, if $g_2 = 10^{-4}$, $G_2 = 0.01G_1$, and $f_2 = 2.5f_1$, and if $g_2 = 10^{-5}$, $G_2 = 3.16 \times 10^{-3}G_1$ and $f_2 = 3.16\ f_1$. This means that to develop the same bubble size at low-g as at one-g the gas flow rate would have to be reduced to 10^{-3} to 10^{-2} that at one-g. Furthermore, the bubble frequency would increase from 2.5 to 3 times so that there would be a proportionally higher surface area for chemical reactions to occur.

Thus, in low-g there would be a significant impact on bubble size, rate of bubbling, rate of bubble coalescing, surface area, terminal velocity, and reaction contact time. Any one of these characteristics could be used to advantage in processes involving flows with bubbles.

2. **Gas Stripping in Liquid Metals:** Gas stripping is used to remove magnesium dissolved in molten aluminum, Ref. 9. This is a common operation in the secondary aluminum remelt recovery business. The $Mg + 2Cl \rightarrow MgCl_2$ reaction produces a less dense dissolved salt which at one-g rises to the top. One of the problems in this industry is that as the magnesium level is reduced below a level of about one weight percent the efficiency decreases rapidly because the chlorine rate is too high for the reaction mass transfer to be effective. Hence, if the process could be carried out in such a way that the gas throughput could be reduced to obtain more efficient contacting then the conversion could be improved. Since the reduction of gas rate also results in larger surface area at low-g for the same bubble size then it is conceivable that this could lead to process improvements. Low bubble rise velocity would also help to maintain spherical shapes and avoid deformed bubbles which result in optimum mass transfer coefficients.

The consequences of this concept could be the elimination

of expensive pumps that are presently needed to ensure good gas-liquid contacting with molten aluminum. The complete removal of magnesium with low chlorine consumption would result. Furthermore, environmental pollution would be non-existent because all the chlorine would be consumed.

This example is specific to one metal but is also generic in the sense that it applies to any in which a gas is used to sweep through a liquid to remove a dissolved chemical. Again, it should be emphasized that this description does not imply that aluminum demagging should be done in space, but it does show how limitations at one-g could be circumvented at low-g.

3. Flooding in Packed Towers: In countercurrent gas-liquid flow in a packed tower (see Fig. 1) used for gas absorption there is a phenomenon called flooding. This occurs when the gas velocity exceeds a critical level. At this point, the liquid cannot fall at a rate equal to the input feed rate. Then the gas flow is reduced and surging results which upsets the column behavior.

The relationship at flooding is such at, G, the vapor flow rate is proportional to $g^{1/2}$, Ref. 10. At a fixed ratio of liquid to gas feed rate the result would be that each of these is proportional to $g^{1/2}$. Hence, at low-g absorption could be obtained at much lower liquid and gas throughput. At low-g there would be significant differences in process vessel sizing and feed. However, there would be an associated reduced throughput.

Absorption is used to remove pollutants from gases. A prime example is NH_3 or SO_2 scrubbing from air using water in both cases. This is an often-used unit operation in chemical processing. It is also used to remove reaction products from catalytic reactors with water as the quench, scrubbing liquid.

Manufacturers are Corning Glass, Glitsch, Pfaudler, Otlo H. York.

4. Distillation: This is the most ubiquitous of all separation schemes in industry. It is used to purify most bulk chemical liquids and gases. It is a process based on applying heat to a mixture to separate one component from another based on their relative vapor pressures. Input of heat enriches the vapor

in the more volatile component and does the opposite for the heavier or less volatile one. Various schemes for using towers containing plates, packings, etc. are used to improve the separation efficiency.

The use of the heat pipe principle to separate a methanol-water mixture in a horizontal distillation column is described in Ref. 11. The process is said therein to be a zero-gravity distillation, but it merely did not use gravity to separate the vapor from the liquid due to buoyancy. The separation was affected by using capillary wicks. The result was that a short horizontal column accomplished what normally requires a tall vertical tower nine times as long.

Application of the heat pipe principle to "outer space" applications is referred to but not developed in that paper. Extension to low-g conditions where thermocapillary flow and surface-tension effects predominate would be worth exploring. This could lead to purification, preparative, and recycling schemes in space which are efficient and space-saving. The same may accrue on earth as well.

5. Contact Efficiency: In distillation on earth it has been found, Ref. 10, that contact efficiency between gas and liquid on a plate in a distillation column can have different values depending on frothing. This is related to surface tension differences of species in the mixture. Apparently, the role of surface-tension gradients is important in governing stability of froths and foams. Froth stability results when surface-tension flow causes liquid to flow from a low surface-tension region to a higher one. This occurs when the more volatile component (higher vapor pressure) has the lower surface tension. This phenomenon has been found for gas-liquid contact in packed wetted wall columns. The froth stability is called a positive system and gives high efficiencies. However, the result is loss in capacity due to greater tendency for flooding.

This phenomenon is similar to what is expected at low g, i. e., surface-tension flow predominates over buoyancy driven flow. It should be possible to analyze the reasons for both positive and negative systems and their consequences on through-put at one-g as well as the implications for distillation at low-g.

Distillation is so common that it can be found anywhere from the hillsides of West Virginia, producing 200 proof moonshine to hundred foot high towers in refineries. It is a big business and any improvement in design or understanding means of circumventing shortcomings on earth would be desirable.

Columns are made by Glitsch, Koch Engineering, Pfaudler, Chem Pro, and Distillation Engineering.

Contact efficiency in gas-liquid, liquid-solid, gas-solid, and liquid-liquid heterogeneous reactions could also be improved in low-g because of reduced sedimentation and buoyancy convection. Suspended gas, liquid, or solid particles would have longer residence times and could also possibly control the position of chemical equilibrium by not shifting to completion by the LeChatlier principle (mass action).

6. **Gas-Liquid Chromatography (GLC):** This is a separation process used in chemical analysis and in preparing high purity fine chemicals. It became so popular after its introduction in 1955 that almost all chemists use it presently. It is a batch process wherein a solid bed containing a high-surface area adsorbent is wetted with a solvent liquid of low volatility. The bed usually resides in a long capillary tube, sometimes hundreds of feet long coiled up inside a constant-temperature oven. The sample liquid or gas is injected and heated to gasify it. Then, by differences in the solubility of the gas components in the liquid the sample is separated into its fragments. As the gases slowly elute one after the other in the carrier gas the sample analysis is indicated as an upset of a balanced Wheatstone bridge containing a sensitive detector based on, for example, thermal conductivity.

At low-g thermocapillary flow may become important. Since this is a key in GLC it would be appropriate to consider how GLC might be improved further at one-g or how it might perform at low-g.

All analytical laboratories use this process. In some cases in biological labs it is used to prepare sample sizes or even saleable quantities of chemicals which cannot be purified in any other way.

7. **Super Critical Fluid Extraction (SCF):** In this process fluids are used at or near the critical point where they have unusual solvency characteristics to purify or extract one phase from another. Interest in the process is being shown in the fuel and food industries, single-cell protein manufacture, recovery of waste materials, desalination, and chromatographic separations, see Refs. 12 and 13.

Near the critical point all factors for buoyancy-driven flows are maximized at one-g so that rather strong remixing flows can be expected. Thus, operation at low-g might be extremely beneficial. The fluid flow aspects have essentially been neglected and mostly experiments are run based on empirical methods. Studies should be made of the flows to minimize turbulence and remixing at the disengaging zones where the temperature and pressure are reduced to obtain two phases.

This is a new but rising technology and an industrial consortium has funded research at NBS-Boulder. Active work is ongoing at MIT, The University of Delaware and several private research groups. Kerr McGee has an industrial process called "ROSE" for purifying heavy residual oil. Sohio is active in practical purification and extraction studies.

8. **Low Density Plastics and Ceramics:** Low density polymers, ceramics, and composites are becoming important for their application in building, insulation, retractories and, electrochemistry.

By processing at low-g with gas trapped in bulk pores due to reduced buoyancy prior to phase change from liquid to solid, it should be possible to obtain low bulk density shapes. If the pores are interconnected it might be possible to bring the shapes back to earth where degassing would occur and the resulting solids would be microporous and serve as gas-liquid permeable separators. If they are formed with non-connected pores at low-g, the gas could be selected to have low (or high) heat transfer characteristics and then be used on earth for either thermal conductors or insulators.

The technique should work in principle with any precursor liquid, such as polymer or ceramic prior to solidification where bubbles are trapped. A good example would be formation of a

microporous separator for fuel cells or batteries, Ref. 14. Companies in plastic composites or possibly "high-tech" ceramics should be interested.

9. Polymer Devolatilization: All polymer production requires a post treatment to remove residual small molecule unreacted monomer or solvent. Bubble transport through the liquid (or solid) is the key step in devolatilization (DV).

Elementary steps in all DV processing are, Ref. 15: interfacial generation, interfacial mass transfer and surface renewal. The gas pressure in the submerged bubble must exceed the hydrostatic pressure of the surrounding liquid in order to escape. In the absence (or reduction) of hydrostatic pressure in low-g the bubble pressure is controlled by surface tension of the surrounding liquid. In addition, surface-tension driven convection will govern the release of the bubbles. Thus, DV processing would be different at low-g. This is not tc imply that there is necessarily an advantage at low-g. However, it would provide an alternate reaction environment where the roles of gravity and surface tension are the reverse of what they are at one-g. This might lead to a new processing technology.

Polymer processing is big business for those firms making thin films, containers, car bodies, and liquid packaging. Especially important are those end applications where contamination of food, medicine, body lotions, etc. by leaching of toxic monomers are possible. Most all large petrochemical processors are also involved in this type of operation. Manufacturers of bottles, food wrapping, etc. would also be included.

10. Mechanics of Aerosols: Aerosols coalesce and settle as a consequence of collisions, surface charges, surface tension, and gravity. In low-g, convection is drastically reduced, so that the frequency and intensity of collisions is reduced. On the other hand the reduction of shear forces reduces the disruption of chains of particles, such as soot. In any event, the reduction of gravity reduces settling except that due to other field forces, and aerosols should be much longer-lasting and uniform.

The characteristics and behavior of aerosols in low-g are

of interest and the persistence of dispersed liquids and solids in the atmosphere of a space vehicle may be either desirable or undesirable for health and safety.

11. Foam Formation, Stability, and Behavior: Foams are destroyed by gravity and surface tension. In low-g uniform foams should be easier to form and maintain. Hence, it may be possible to construct unique metal or plastic materials or structures by foaming and freezing in space. It should also be possible to study the fundamental characteristics of foams under more controlled and stable conditions than on earth and to observe the fundamental role of surface forces in the absence of the complications of gravity.

Experiments could be performed in which liquids are first foamed and then solidified. The foaming could be obtained by injection of gas into a flowing liquid stream, followed by a mechanical agitation to achieve isotropy and perhaps a controlled size of bubbles. The foam can then be solidified by cooling and freezing or by chemical reaction (for polymers). The effects of surfactants can also be examined.

12. Gases and Liquid Jets: Gas and liquid jet systems play an important role in many processing operations. In the majority of practical situations there is interest in the interaction of a jet with a dissimilar fluid. The jets may be used for heat transfer, agitation, or reactions (like oxidization). The breakup of the jets to bubbles and droplets plays an important role in the processes. The characteristics and nature of jets interacting with dissimilar fluids can be different in low-g due to the differences in buoyancy and interfacial effects and thus the processes may be significantly altered.

13. Nucleation and Cluster Phenomena: In its formation from a parent phase, a new phase evolves through an embryonic (nucleation) stage and grows through various cluster stages before it reaches bulk dimensions. Nucleation and cluster processes are basic to numerous areas of science and technology such as mineralogy, meterology, electrodeposition, and materials processing, including the manufacture of partly crystallized glasses.

Nucleation can occur spontaneously in the bulk or on free

surfaces of pure phases. More commonly, however, nucleation is stimulated by inhomogeneities (particulates, container walls, etc.) before spontaneous nucleation occurs. At the embryonic stage of phase transitions, thermal fluctuation energies completely mask the local effect of gravity. For the growth of cluster sizes at or above one micron, however, gravitational and other bulk flow phenomena can be rate-limiting mechanisms.

The practical achievement and, hence, experimental study of homogeneous nucleation is extremely difficult. The limitations from the omnipresence of particulates and from container walls have been overcome, to some extent, by techniques which suspend low-melting (metallic) drops in inert, buoyant fluids. Yet, most recent experiments on droplets in evacuated drop tubes raised doubts as to whether the undercooling upset the true homogeneous nucleation, Refs. 16 and 17. For larger samples (mm-size) or for samples with lower melting points it is difficult to reach the limit of undercooling in the time available in drop tubes.

To date, studies of cluster phenomena are practically all conducted under conditions in which gravitational effects either directly (sedimentation, differential settling, etc.) or indirectly (interaction with field and thermal environment in limited-size levitation equipment) complicate the experimental conditions. All of these will be different in a low-g environment.

14. Boiling: Although boiling heat transfer is one of the most efficient means of heat removal, the various boiling regimes are not entirely understood. The transition region between the nucleate and film boiling regimes has not been modeled and, consequently, there is little information on how this would be affected by gravity. The same is true for the incipient boiling point as a function of gravity. Nearly all the existing nucleate boiling models and correlations show a gravity dependence which has been inconsistent with existing low- and high-g data. Thus, further experimental clarification of the low-g effects on boiling is needed. In particular, the effect of low-g on each of the regimes associated with pool boiling should be determined. These regimes include incipient boiling, nucleate boiling, peak flux, transition, and film boiling which are shown in Fig. 2 for one-g. This information would have direct implications for many industrial applications. For example, in Fig. 3 the various flow

regimes are shown in vertical tube evaporator. These would obviously be strongly affected by changes in g.

Steady nucleate boiling can occur only as long as there is continual removal of the bubbles formed at the surface. The magnitudes of the various bubble-removal forces depend on both the liquid properties and the physical conditions. A knowledge of the forces associated with bubble attachment, growth, and breakoff in low-g would provide a greater understanding of how gravity affects the nucleate boiling process. Other factors in boiling that will be different in low-g are the bubble microlayer which is directly related to bubble growth and the liquid flows about the bubble. In the latter thermocapillary effects should be dominant.

Although it would appear that if flow rates were sufficiently high, forced convection boiling would not be affected by gravity, nevertheless, some unexpected results were obtained in low-g, Ref. 18. For example, an instability was observed that occurs only in low-g. The flow was intentionally interrupted while heating of the tube was continued and when the flow was restarted, it was not steady. It was postulated that in low-g the bubbles coalesced during the no flow period and, thereby, formed large vapor masses and liquid slugs which altered the liquid-vapor flow characteristics. Also, significant damping of pressure oscillations in a heated flow loop was reported in Ref. 19.

These two examples illustrate that there are differences in heat transfer and flow between one- and low-g even for forced convection boiling. Thus, there is need to define and understand how low-g affects this phenomena.

III. Liquid-Solid

Minimization of sedimentation at low-g is directly related to efficiency of contacting in liquid-solid and gas-liquid-solid processes. Reduction of buoyancy also leads to less stratification of light solid particles on top of a liquid. As a consequence of more uniform suspension of solids in liquids it should be possible to carry out reactions where the solid catalyzes the liquid conversion to a desired product. Another common situation is the three phase catalytic hydrogenation of

organic liquids using suspended metal catalyst particles. In this case it would not matter if the bulk density of the particle were lower or higher than the fluid in which it was suspended. On bubbling hydrogen through the liquid it would be possible to obtain optimum efficiency of the three phase contact. This is a common process in the food industry in making saturated oils from unsaturates. It is also involved in the making of soaps.

1. **Electrophoretic Coating:** This process is used to apply coatings of fine particles suspended in a dielectric medium. The particles migrate in an electric field to the surface of a charged body where they adhere and provide a weakly bonded "green coating." At one-g it is difficult to maintain the dense particles uniformly suspended in the liquid medium because they tend to precipitate out. At low-g this would not be a problem.

2. **Polymerization:** As monomers react to form long chain polymers the molecular weight increases and eventually the reaction product settles out of the liquid at one-g. At low gravity the reaction should be able to proceed to completion.

3. **Catalyst Impregnation:** Catalyst pore impregnation with rare metal chemicals (or any other chemicals) could be improved by capillary flow at low-g. A catalyst is only as good as the degree to which it is uniformly coated on to the solid support. By using capillary flow as a dominant force at low-g it may be possible to achieve greater uniformity.

An adjunct to this is the idea of using a supercritical fluid as the solvent for the active catalytic metal containing chemical. The solid support particles are then uniformly suspended in the supercritical fluid at low-g. By capillary flow the reactive metal impregnates the catalyst support pores. Then the supercritical solvent can be flashed off by reducing the temperature and pressure.

IV. Liquid-Liquid

Binary metal alloys are typically prepared by comelting two metals and then cooling. If they are miscible the solid will be homogeneous. Some binary systems are not homogeneous when prepared this way terrestrially because of the large differences in liquid density. Evidence points to this not being as much a

problem in low-g processing to fill in miscibility gaps.

1. **Silicon Planar Diffusion Sources:** A specific need here is for preparation of silicon planar diffusion sources containing uniform concentrations of metallic dopants. Typically, this might be controlled amounts of Group V elements (P, As, Sb, Bi) in silicon. The planar diffusion sources serve as a supply of dopant elements when put adjacent to a silicon receptor in a furnace at temperatures greater than 1000°C. The dopant boils out of the source and diffuses through the gas gap into the silicon disc next to it. It is important to control the amount and uniformity over the entire surface.

Presently these sources are made in crude powder metallurgy fashion leading to uneven and uncontrolled levels of dopant. By having a miscible alloy formed at low-g an improvement should result in quality and reliability of dopant properties.

2. **Liquid-Liquid Dispersions:** Liquid-liquid dispersions have many applications such as for extraction and for the controlled flow of mixtures of immiscible fluids. Such dispersions are generally destroyed rapidly by gravity so that they are difficult to generate and even harder to study, in any fundamental sense, on earth. In low-g the generation of uniform dispersions and their maintenance should be much easier. The dispersions can be generated by agitation of previously weighted quantities of the two liquids in a closed container. The drop-size distribution and long-time stability can be determined by light scattering. Agitation can be accomplished by stirring or shaking. The effect of surfactants can also be studied.

Another example of such systems is the movement of molten droplets in melts which are of considerable interest in many processing applications. The behavior of liquid droplets in liquids (melts) parallels the behavior of gas bubbles in liquids.

3. **Interface Importance:** In liquid-liquid extraction the role played by the interface is critical. For example, in Ref. 20 anamolous results are reported when the turbulence generated by shaking a separatory funnel led to much improved extraction of a chemical from one liquid phase into another. Since this is related to an increase in surface area and interfacial tension it is suggested therein to examine this at low-g to: (a) see if it

provides greater extraction capabilities with the reduced buoyancy caused turbulence and (b) understand under a controlled environment why it worked. Other more recent work along this same line but still at one-g is reported in Ref. 21, a,b.

A summary of some of the topics discussed above is given below:

Adiabatic Two-Phase Processes

Multiphase Flow
- Flow Regime Delineation
- Pressure Drop
- Equilibrium Configurations

Bubble Motion and Liquid-Gas Interface Interaction
- Bubble Migration Rates
- Breakthrough Phenomena

Bubble Dynamics
- Formation/Detachment Dynamics
- Coalescence Mechanisms

Nonadiabatic Two-Phase Processes

Multiphase Forced Convection
- Heat Transfer Coefficients

Nucleate Boiling
- Boiling Curve
- Burnout Heat Flux
- Unsteady Phenomena

Interfacial Processes
- Condensation

C. **Surface Tension Effects** - Numerous of the above discussed phenomena involved surface-tension effects. Since surface tension becomes a dominant force at low-g those phenomena are expected to be different in spacecraft experiments. In this section several other industrial processes that rely on surface tension will be discussed.

I. Thin Films and Coatings

Increased attention is being focused on thin liquid film phenomena that occur in areas of engineering interest such as foam drainage, drop and bubble coalescence, multiphase flow through porous media, coating processes, biological thin films, sintering, and fabrication processes involved in the microelectronics industry. The recognition of the importance of thin liquid film phenomena in current as well as emerging technologies led to a recent symposium on that subject, Ref. 27.

Thin liquid films will behave quite differently under low-g than one-g, Ref. 23. Thermodynamic studies of such films are based on the assumption that gravity is absent. However, reexamination of experimental observations suggests the possibility that gravity plays a much more important role than has heretofore been suspected. The differences in the behavior of drops or bubbles on a flat and rigid solid surface, spreading of a liquid on a liquid, and of soap bubbles with and without gravity are analyzed in Ref. 23. The effect of gravity is shown to determine the possible existence of thin liquid films at thermodynamic equilibrium.

Flowing thin films in which there is an interplay among viscous, inertial, gravitational, and capillary effects are important in many industrial applications. Absorption into a downflowing liquid film is one of the most important and widely used methods for dissolving gases. Coating flows are used to cover a large surface area with one or more thin, uniform liquid layers. The liquid film is subsequently dried or cured and often serves to protect or decorate the substrate. The film may also serve a more active function, such as the recording of information. In industrial applications, the layer thickness may have to be very thin and highly accurate. For productivity reasons a high speed application may be required and several discrete layers may have to be applied simultaneously. As a result of such demands attempts to use a specific coating process for a given application frequently fail. The liquid layer may not be continuous and, if it is, waves or streaks may occur.

The dozens of coating devices in use attest to the practical difficulty of the coating problem, Refs. 24 and 25. Even a cursory review of that material makes it evident that

basic science has not had a great deal to do with the development of the technology. This is not to say that useful research on coating flows has not been done. Rather, as in many other areas of technology, largely empirical developments have outpaced scientific understanding.

Recent work on capillarity effects done in conjunction with containerless processing at low g has given greater understanding of such effects and could be useful in improving coating technology. Furthermore, the dominance of surface tension under that condition could be very beneficial. For example, surface tension is relied on for coating processes so that terrestrially the films must be thin to overcome gravity. Thicker films, layers and coatings could be possible at low g. There is also the possibility that multiple layers could be applied simultaneously at low g whereas they would be too thick at one g.

II. Fibers and Filaments

The formation and stability of fibers and filaments also depend strongly on surface tension. Applications in a wide range of industries have recently been enumerated in Ref. 26. These phenomena may well be significantly different at low g where surface tension is dominant.

CONCLUSIONS

The survey of many industrial processes has indicated that most industrial processes are developed empirically. Little attention has been given to the role of gravity on the processes. With the advent of the space program some thought was given in some instances to space-oriented research, but there is no real enthusiasm for it. There is a great need for developing a scientific and technical data base on which to demonstrate the advantages for improving processing both terrestrially and at low g.

Numerous industrial processes and phenomena are identified herein which involve at least gravity and/or surface tension forces. These are in no way to be considered to be all inclusive. There are many others with similar characteristics that could be cited. However, the wide diversity of industries and processes is well represented. Indications of the potential

benefits of low g are given.

This report can well serve as a basis for defining a broader low-g research program and, at the same time, help target those industries which might be convinced to give more scientific scrutiny to their processes in order to improve their competitiveness.

REFERENCES

1. Considine, D. M., Edit.: Chemical and Process Technology Encyclopedia, McGraw-Hill, 1974.

2. Bravo, J. L., Fair, J. R., Humphrey, J. L., Martin, C. L., Seibert, A. F., and Joshi, S.: Fluid Mixture Separation Technologies for Cost Reduction and Process Improvements, Hoyes Publications, 1986.

3. Walters, S.: Tapping the Resources of a New 'Continent,' Pt. 1-Materials Processing, Mechanical Engineering, ASME, June 1981.

4. Lucas, W. R.: Chemistry in Space, American Chemical Society, 297th National Meeting, April 1984.

5. Bell, A. T.: Research Opportunities in Catalysis, Chemical Engineering Progress, Vol. 83, No. 2, Feb. 1987.

6. Cocke, D. L.: Heterogeneous Catalysis by Amorphous Materials, Journal of Metals, Feb. 1986.

7. Lydersen, A. L.: Mass Transfer in Engineering Practice, John Wiley & Sons, 1983.

8. Turkdogan, E. T.: Physical Chemistry of High Temperature Technology, Academic Press, 1980.

9. Mangalick, M. C.: Demagging in the Secondary Aluminum Industry, Journal of Metals, June 1975.

10. King, C. J.: Separation Processes, McGraw-Hill, 1971.

11. Seok, D. R. and Hwang, S.-T.: Zero Gravity Distillation Utilizing the Heat Pipe Principle (Micro-Distillation), AIChE Journal, Vol. 31, No. 12, Dec. 1985.

12. Schneider, G. M. Stahl, E., and Wilke, G., Edits.: Extraction with Supercritical Gases, Verlag Chemie, 1980.

13. Coenen, H. and Kriegel, E.: Applications of Supercritical Gas Extraction Processes in the Food Industry, German Chemical Engineering, Vol. 7, pp. 335-344, 1984.

14. Suh, N. P., Coltan, J. and Kumar, V.: Nucleation and Production of Microcellular Foam, Polymer Research Annual Rept., MIT, March 1986.

15. Biesenberger, J. A. and Sebastian, D. H.: Principles of Polymerization Engineering, Wiley, 1983.

16. Drehman, A. J. and Turnbull, D.: in "Materials Processing in the Reduced Gravity Environment in Space," G. E. Rindone, Edit., p. 81, Elsevier, 1982.

17. Lacy, L. L. et al.: Journal of Crystal Growth, Vol. 51, 1981.

18. Pappel, S. S.: An Instability Effect on Two-Phase Heat Transfer for Subcooled Water Flowing Under Conditions of Zero Gravity, Paper No. 2548-62, American Rocket Society, Space Power Systems Conference, Santa Monica, Calif, 1962.

19. Feldmanis, C. J.: Pressure and Temperature Changes in Closed Loop Forced Convection Boiling and Condesning Processes Under Zero Gravity Conditions, Proceedings of the Inst. of Environmental Sciences, San Diego, Calif., 1966.

20. Allen, K. A. and McDowell, W. J.: Anomalous Solvent Extraction Equilibria Due to Violence of Agitation, Journal of Physical Chemistry, Vol. 64, 1960.

21. Abstracts of Papers, 191st American Chemical Society Meeting, New York, Aril 1986.

    a. Aprahamian, E. and Freiser, H.: The Role of the Interface in the Extraction of Transition Metal Dithizorates, INDE 244

b. Skelland, A. H. P. and Xien, H.: Dispersed Phase Resistance to Mass Transfer in Agitated Liquid-Liquid Systems, INDE 273.

22. Krantz, W. B., Wasan, D. T. and Jain, R. K., Edits.: Thin Liquid Film Phenomena, AIChE Symposia Series, Vol. 82, No. 252, AIChE, New York, 1986.

23. Marmur, A.: The Effect of Gravity on Thin Fluid Films, Journal of Colloid and Interface Science, in press.

24. Higgins, D. G.: Coating Methods, in Encyclopedia of Polymer Science and Technology, Vol. 3, 765-807, Wiley, 1965.

25. Booth, G. L.: Coating Equipment and Processes, Lockwood, N. Y., 1970.

26. Schummer, P. and Tebel, K. H.: German Chemical Engineering, Vol. 5, 209, 1982.

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TABLE 1 *Separation Operations Classified on Basis of Phases of Components in Starting Mixture*

Liquid-Gas	Gas-Gas	Gas-Solid
Gravity settling	Low-temperature distillation	Gravity settling
Impingement separation	Absorption	Impingement separation
Cyclone separation	Adsorption	Cyclone separation
Foam breaking	Gaseous diffusion	Electromagnetic separation
Drying	Thermal diffusion	Filtration
Boiling	Electromagnetic separation	
Condensation	Chromatographic separation	
	Condensation	
Liquid-Liquid	**Liquid-Solid**	**Solid-Solid**
Distillation:	Sedimentation	Size classification
Rectification	Thickening	Screening
Azeotropic	Clarifying	Dense-medium separation:
Extractive	Filtration	Jigging
Molecular	Centrifugation	Tabling
Extraction:	Drying	Magnetic separation
Solvent	Spray drying	Electrostatic separation
Precipitative	Evaporation	Flotation
Dialysis	Crystallization	Sublimation
Electrodialysis	Prilling	Freeze-drying
Thermal diffusion	Graining	
	Leaching	
	Expression	

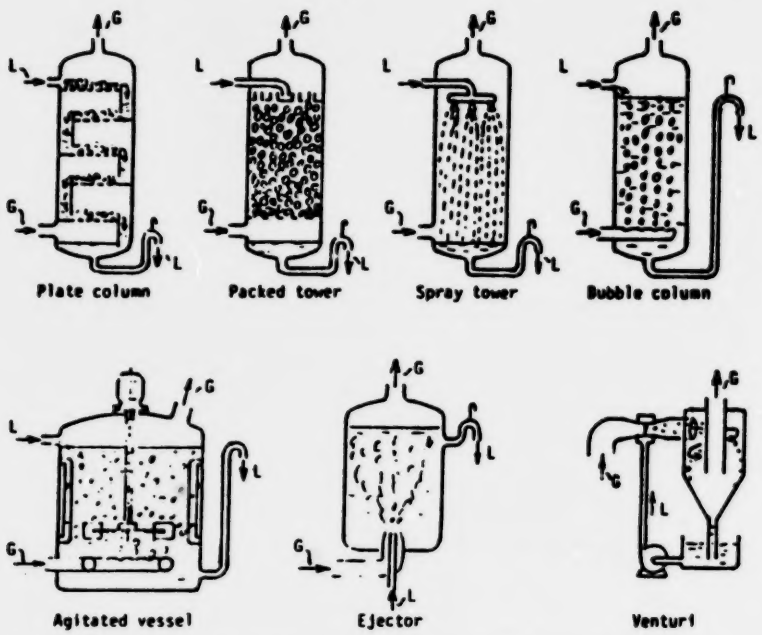

Figure 1 Schematic drawings of main types of gas absorption equipment

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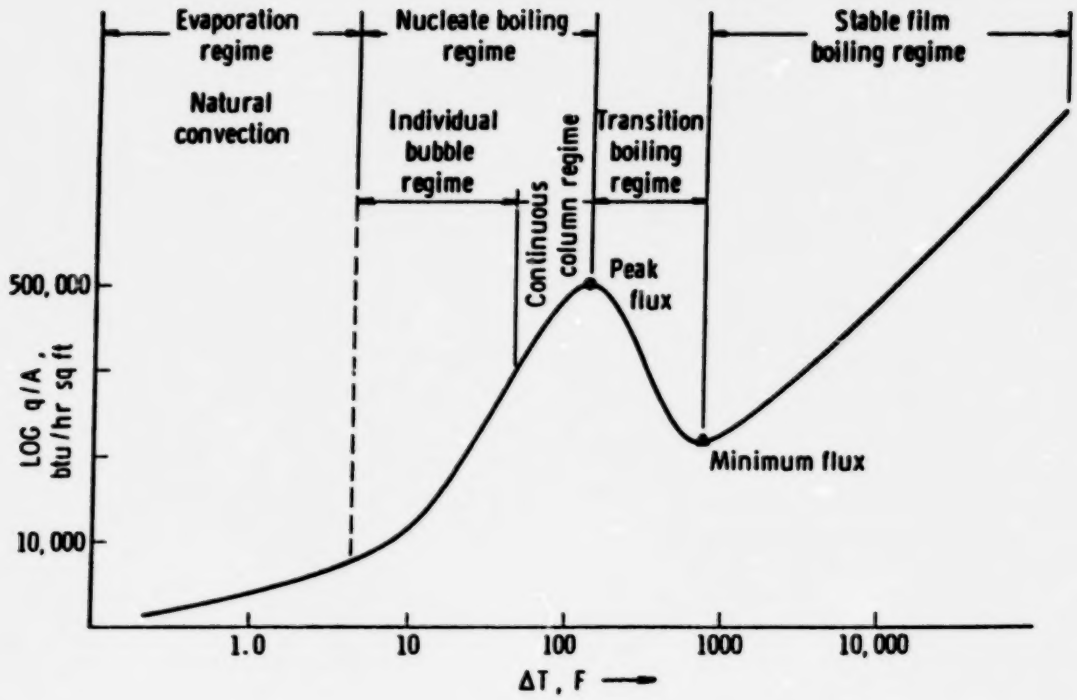

Figure 2 Typical boiling curve for water under $1-g_0$ conditions

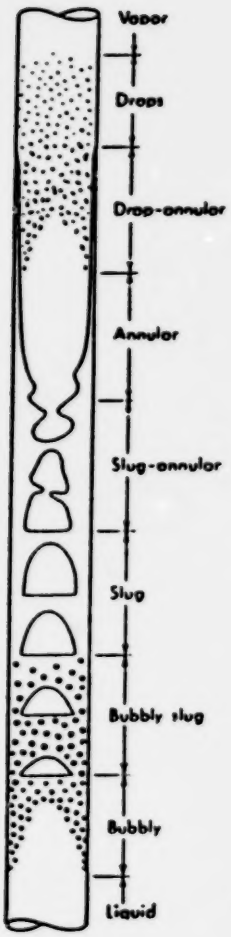

Fig. 3 Approximate sequence of flow patterns in a vertical tube evaporator.

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OF POOR QUALITY

BIBLIOGRAPHY

A. Space Research:

1. Battrick, B. T., ed.: Processing and Manufacturing in Space, Symp. at Frascati, Italy, 3/74; N 75 - 19285, 1974.

2. Steg, L. ed.: Materials Sciences in Space with Application to Space Processing, Vol. 52, Prog. in Astronautics and Aeronautics, AIAA, 1977.

3. O'Neill, G. K., ed.: Space Based Manufacturing from Nonterrestrial Materials, Vol. 57, ibid, 1977.

4. Silverman, S., ed.: Applications of Space Flight in Materials Science and Technology, NBSSP-520, 1978.

5. Criswell, D. R.: Extraterrestrial Materials Processing and Construction, NSR 09-051-001, No. 24, NASA Johnson Center, Texas, 1978..

6. Slichter, W. P., ed.: Materials Processing in Space, NCR Rept., 1978.

7. Guyenne, T. D., ed.: Material Sciences in Space, 3rd European Symp., ESA SP-142, 1979.

8. Naumann, R. J., ed.: Materials Processing in Space: Early Experiments, NASA SP-443, 1980.

9. Sychev, V. V., Complex Thermodynaic Systems, Mir. Publ., Moscow, 1981.

10. Rindone, G. E., ed.: Materials Processing in the Reduced Gravity Environment of Space, Proceed. MRS Ann. Mtg. 1981, North Holland, 1982.

11. O'Leary, ed.: Space Industrialization, Vol. 1, CRC Press, 1982.

12. Ibid, Vol. 2, 1982.

13. Kops, L., ed.: Manufacturing in Space, ASME Meeting, 11/83, PED Vol. 11, ASME, 1985.

14. Guyenne, T. D., ed.: Materials Sciences Under Microgravity, 4th European Symp., ESA SP-191, 1983.

15. Dunbar, B. J., ed.: Materials Processing in Space, Adv. in Ceramics, Vol. 5, Amer. Ceramic Soc., Columbus, Ohio, 1983.

16. Avduyevsky, V. S., ed.: Scientific Foundations of Space Manufacturing, Mir. Publ., Moscow, 1984.

17. Guyenne, T. D.: Materials Sciences Under Microgravity: Results of Spacelab 1, 5th European Symp., ESA SP-222, 1984.

18. Jernigam, C. M., ed.: Second Symposium on Space Industrialization, NASA Conf. Publ. 2313, 1984.

19. Feuerbacher, B., ed.: Materials Sciences in Space, Springer Verlag, NYC, 1986.

20. McElroy, J. H., ed.: Space Science and Applications: Progress and Potential, IEEE Press, NYC, 1986.

21. Farrell, P. V.: Droplet Vaporization in Supercritical Pressure Environments, Microgravity Materials and Fluid Sciences, ed. L. G. Napolitano, Acta Astronautica, 13 (11/12), 673 (1986).

22. Norton, D. J., ed.: Symposium on Microgravity Fluid Mechanics, ASME, FED-Vol. 42, New York, 1986:

a. Krotiuk, W. J. and Antoniak, Z. I.: The Development of Two-Phase Computer Codes for Microgravity Applications, p. 1.

b. Peterson, G. P. and Annamalai, K.: A Differential Approach to Heat Pipe Priming in Microgravity, p. 25.

c. Concus, P.: Equilibrium Fluid Interfaces in the Absence of Gravity, p. 37.

23. Matsuo, H., ed.: Proceedings of the Fifteenth International Symp. on Space Technology and Science, Agne Publ., Inc., Tokyo, Japan, 1986.

a. Poletti, G.: A Microgravity Experiment to Measure Surface Forces and Surface Energies in Solids, p. 2117.

b. Chun, C-H.: Thermocapillary Flow in Surroundings of a Bubble Under a Heated Wall, p. 2127.

c. Siekmann, J. and Szymaczyk, J.: On the Thermocapillary Motion of a Bubble in a Low Gravitational Environment, p. 2137.

d. Azuma, H., Yoshihara, S., Ogiwara, S., and Ogawa, A.: Interaction Between a Couple of Bubbles in Thermal Gradient, p. 2149.

e. Ryazantsev, Y. S.: Capillary Motion of Droplet Induced by Surface Chemical Reaction, p. 2155.

f. Kuwahara, K., Morioku, M. Ochiai, J. and Enya, S.: Fundamental Study of Marangoni Convection in Bridgman Method, p. 2161.

B. Separations:

1. King, C. J.: Separation Processes, McGraw Hill, NYC, 1971.

2. Considene, D. M., ed.: Chemical and Process Technology Encyclopedia, McGraw Hill, NYC, 1974.

3. Schweitzer, P. A., ed.: Handbook of Separation Techniques for Chemical Engineers, McGraw Hill, NYC, 1979.

4. Hsu, H. W.: Separations by Centrifugal Phenomena, Wiley and Sons, NYC, 1981.

5. Denson, C. D.: Stripping Operation in Polymer Processing, Adv. in Chemical Engineering, Wei, ed.: Academic Press, Vol. 12, p. 61 (1983).

6. American Chemical Society Abstracts of Papers, NY Meeting 4/86, Industrial and Engineering Chem. Section, 1st Intl. Conf. on Separations Science and Technology.

7. Bravo, J. L. et al. eds.: Fluid Mixture Separation Technologies for Cost Reduction and Process Improvement, Noyes Publication, Park Ridge, NJ, 1986.

8. Lydersen, A. L.: Mass Transfer in Engineering Practice, Wiley, New York, 1983.

9. Perry, R. H., ed.: Chemical Engineers Handbook, 4th Ed., McGraw Hill, New York, 1963.

10. Seok, D. R. and Hwang, S-T.: Zero Gravity Distillation Utilizing the Heat Pipe Principle (Micro Distillation), AIChE J., 31(12), 2059 (1985).

11. Allen, K. A. and McDowell, W. J.: Anomalous Solvent Extraction Equilibria Due to Violence of Agitation, J. Phys. Chem., 64, 877 (1960).

12. Abstracts of Papers: 191st American Chemical Society Meeting, New York, April, 1986.

a. Bier, M., Egen, N. B., Twitty, G. E., Mosher, R. A., Thormann, W.: Preparative Electrophoresis Comes of Age, INDE 88.

b. Thormann, W., Mosher, R. A. and Bier, M.: Separations by Capillary Electrophoresis, INDE 89.

c. Aprahamian, E. and Freiser, H.: The Role of the Interface in the Extraction of Transition Metal Dithizonates, INDE 244.

d. Skellund, A. H. P., Xien, H.: Dispersed Phase Resistance to Mass Transfer in Agitated Liquid-Liquid Systems, INDE 273.

13. Hord, J.: NBS Center for Chemical Engineering (CCE) and U. of Arizona's Center for Separation Science (CSS) Sign Coop. Research Agreement, CCE Newsletter, Nov., 1986.

C. Supercritical Fluid Extraction

1. Russell, J. H. and Pattle, R. E.: Dispersing and Solution in Fluids Near the Critical Region, J. Appl.Chem. Biotechnol., 21, 174 (1971).

2. Eggers, R.: Large Scale Industrial Plant for Extraction with Supercritical Gases, Angew Chem. Int. Ed., Engle., 17. 751 (1978).

3. Hubert, P., Vitzthum, O. G.: Fluid Extraction of Hops, Spices and Tobacco with Supercritical gases, Angew, Chem. Int. Ed. ,Engle, 17, 710 (1978).

4. Schneider, G. M.: Physicochemical Principles of Extraction with Supercritical Gases, Angew, Chem. Int. Ed. Engl. 17, 716 (1978).

5. Bott, T. R.: Supercritical Gas Extraction, Chem and Industry, 15 March 1980.

6. Kurnik, R. T., Reid, R. C.: Solubility of Solid Mixtures in Supercritical Fluids, Fluid Phase Equilibria, 8/93 (1982).

7. Paulaitis, M. E., Krukonis, V. J., Kurnik, R. T., and Reid, R. C.: Supercritical Fluid Extraction, Rev. Chem. Eng., 1(2), 179 (1983).

8. McHugh, M. A. and Krukonis, V. J.: Supercritical Fluid Extraction - Principles and Practice, Butterworths, Boston, 1986.

9. Schmitt, W. J. and Reid, R. C.: Solubility of Monofunctional Organic Solids in Chemically Diverse Supercritical Fluids, J. Chem. Eng. Data, 31, 204 (1986).

10. Sengers, JMHL, Morrison, G. et al., Thermodynamic Behavior of Supercritical Fluid Mixtures, Int. J. Thermophysics, 7(2) 231 (1986).

11. Subramaniam, B. and McHugh, M. A.: Reactions in Supercritical Fluids - A Review, Ind. Eng. Chem Process Des. Dev., 25 (1986).

12. Schneider, G.M., Stahl, E., Wilke, G.: Extrction with Supercritical Gases, Verlog Chemi, Deerfield Beach, Fl, 1980.

D. **Critical Point Phenomena**

1. Becker, H., Grigull, V.: Measurement of the Thermal Diffusivity and Conductivity of CO_2 in the Critical Region by Holographic Interferometry, Proc. 7th Symp. on Thermophysical Properties, ASME, NYC, 1978.

2. Sengers, J. V. and Moldover, M. R.: Critical Phenomena Experiments in Space, Flugwiss, Weltraumforsch 2(6) 371 (1978).

3. Moldover, M. R., Sengers, J. V., Gammon, R. W. and Hocken, R. J.: Gravity Effects in Fluids Near the Gas-Liquid Critical Point, Rev. Mod. Phys., 51 (1) 79 (1979).

4. Sengers, J. V., van Leeuwen, J. M. J.: Critical Phenomena in Gases in the Presence of Gravity, Int. J. Thermophysics, 6(6) 545 (1985).

5. Albright, P. C., Sengers, J. V. et al., : A Crossover Description for the Thermodynamic Properties of Fluids in the Critical Region, Int. J. Thermophysics, 7(1) 75 (1986).

6. van Leeuwen, J. M. J. and Sengers, J. V.: Gravity Effects on the Vapor-Liquid Interface Very Close to the Critical Temperature, Physica, 132A, 207 (1985).

E. **MIT Industrial Liason Program**

1. Research at MIT 1986 - 1987 - Directory.

2. Research in Materials - Annual Report, Jan. 1986.

3. Polymer Research Annual Report, March, 1986.

4. Materials Processing Center Annual Report, 1985-1986.

F. **Journals**

1. Journal of Contemporary Business, Enterprise on the Enterprise, 7(3) 1-199 (1978).

2. Commercial Space, Spring, 1986.

3. Ibid, Oct.-Nov., 1986.

4. Advanced Materials and Processes, Space Processing, 2(4), 20-59 (1986).

5. Guyenne, P.: Rethinking Space Business, High Technology, 6(6), 38 (1986).

6. Materials for Economic Growth, Sci. Amer., 255(4), 50-203 (1986).

G. Miscellaneous Journal Proceeding Articles

1. McCutchan, R. T.: Chemical Engineering in the Lunar Environment, Aerospace Chemical Engineering, Simkin, D. J., ed., AIChE Sym. Ser, 62(61), 225 (1966).

2. Wopersnow, W. et al.: Electrolytic Hydrogen Generation Under Zero Gravity, Z. Flugwiss Weltraumforsch 2(5), 342 (1978).

3. Bewersdorff, D.: Physical Basis for Experiments Under Microgravity, Z. Flugwiss Weltraumforsch, 2(6), 365 (1978).

4. Hodes, E. et al.: Production of an Al-Pb Alloy Under Microgravity, Z. Flugwiss Weltraumforsch, 2(5),

5. Franke, B. et al.: Design and Performance of the TEXUS, Materials Science Payload, Z. Flugwiss Weltraumforsch, 2(5), 329 (1978).

6. Waldron, R. D., Erstfeld, T. E., Criswell, D. R.: The Role of Chemical Engineering in Space Manufacturing, Chem. Eng., p. 80 (12 Feb. 1979).

7. Walters, S., Engineering in Space, Pt. 1, Materials Processing, Mech. Eng., 103(6), 26 (1981).

NASA
National Aeronautics and Space Administration

Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
NASA CR-182140		

4. Title and Subtitle	5. Report Date
Industrial Processes Influenced by Gravity	June 1988
	6. Performing Organization Code

7. Author(s)	8. Performing Organization Report No.
Simon Ostrach	None
	10. Work Unit No.
	142-50-10

9. Performing Organization Name and Address	11. Contract or Grant No.
Case Western Reserve University Department of Mechanical and Aerospace Engineering Cleveland, Ohio 44106	C-21066-G
	13. Type of Report and Period Covered
12. Sponsoring Agency Name and Address	Contractor Report Final
National Aeronautics and Space Administration Lewis Research Center Cleveland, Ohio 44135-3191	14. Sponsoring Agency Code

15. Supplementary Notes

Project Manager, Anthony F. Ratajczak, Office of Interagency and Industry Programs, NASA Lewis Research Center.

16. Abstract

In considering new directions for low-gravity research with particular regard to broadening the number and types of industrial involvements, it is noted that transport phenomena play a vital role in diverse processes in the chemical, pharmaceutical, food, and biotech industries. Relatively little attention has been given to the role of gravity in such processes. Accordingly, numerous industrial processes and phenomena are identified which involve gravity and/or surface tension forces. Phase separations and mixing are examples that will be significantly different in low-gravity conditions. This report is intended to serve as a basis for expanding the scope of the low-gravity research program and to indicate to industry the potential benefits of such research.

17. Key Words (Suggested by Author(s))	18. Distribution Statement
Microgravity Industrial processes	Unclassified - Unlimited Subject Category 29

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No of pages	22. Price*
Unclassified	Unclassified	45	A03

NASA FORM 1626 OCT 86

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